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Laboratory Evaluation of Fusion-Bonded Epoxy Coatings for Civil Works Applications

by

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This study investigates safer, more cost-effective alternatives to U.S. Army Corps of Engineers paint specification C-200A, *Coal Tar Epoxy Coating*, which is used to protect steel sheet piling. Fusion-bonded epoxy, a nonpolluting shop-applied coating, was evaluated in laboratory tests as a potential replacement for C-200A. Laboratory tests that included salt and fresh water immersion, cyclic salt fog/ultraviolet (UV) condensation, impact resistance, and cathodic disbondment were conducted on four fusion-bonded epoxy and two control coating systems.

Fusion-bonded epoxy coatings have excellent resistance to impact and cathodic disbondment. Resistance to corrosion in fresh and salt water immersion and in cyclic salt fog/UV-condensation exposures was comparable to the control coating systems. Based on the results of the laboratory tests, a field evaluation of fusion-bonded epoxy is recommended.



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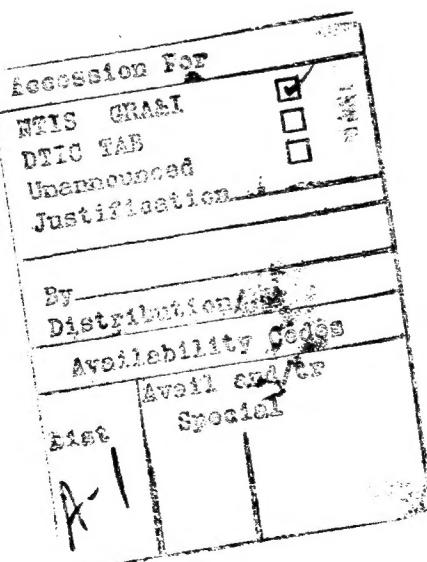
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Foreword

This study was conducted for the Electrical and Mechanical Branch, Engineering Division, Directorate of Civil Works, Headquarters U.S. Army Corps of Engineers (HQUSACE), under Civil Works Investigations and Studies (CWIS) Work Unit 31205, "Developing High Performance Coatings." The technical monitors were Robert Kinsel and John Gilson, CECW-EE.

The research was performed by the Engineering and Materials Division (FM) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Timothy D. Race. Dr. Paul Howdyshell is Chief, CECER-FM, and Alan W. Moore is Acting Chief, CECER-FL. The USACERL technical editor was Thomas E. Rice, Information Management Office.

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1 Introduction

Background

Coal tar epoxy coating C-200A is used for a variety of civil works applications. Civil Works Guide Specification (CWGS) 09940, *Painting: Hydraulic Structures and Appurtenant Works* (1993) recommends C-200A for buried steel pipe and tanks, resistance to damage caused by marine fouling, fresh and salt water immersion, hydraulic piping, marine atmospheric exposure, and pilings. Steel pilings are perhaps the most important use within the U.S. Army Corps of Engineers for coal tar epoxy coatings. CWGS-09940 notes that C-200A paint systems 6 and 6-A-Z should be used to coat (prior to driving) underground, underwater, and incidental atmospheric-exposed sections of steel piling where protection is deemed necessary.

Coal tar epoxy coatings have good impact and abrasion resistance. As with most epoxy coatings, they provide good long-term protection in immersion because of their excellent barrier properties. Corrosion protection can be further enhanced with the addition of a zinc-rich primer. C-200A is a heavy-bodied material with excellent sag resistance allowing very thick coating films to be applied in one application. Good surface preparation, normally Steel Structures Painting Council (SSPC) SP-6, *Commercial Blast Cleaning* (1991) or better is required to achieve proper coating performance. CWGS-09940 calls for SSPC SP-5, *White Metal Blast Cleaning* (1991) for coal tar epoxy systems 6 and 6-A-Z. Coal tar epoxy is applied in the shop and in the field.

The composition of paint C-200A is described by SSPC Paint Specification No. 16, *Coal Tar Epoxy-Polyamide Black (or Dark Red) Paint* (1991). The paint consists of epoxy and polyamide resins, coal tar pitch, an accelerator, solvents, and rheological modifiers. While each of the components has associated hazards, coal tar pitch may be especially hazardous. The adopted threshold limit value for coal tar pitch volatiles is a low 0.2 mg/cm³ expressed as a time-weighted average (American Conference of Governmental Industrial Hygienists, 1989-1990). Coal tar pitch volatiles are a confirmed human carcinogen as well. While most organic coating materials are far from benign, these two factors warrant the investigation of alternative technologies to replace or supplement the use of Corps of Engineers paint specification C-200A. Safe handling practices for epoxy coatings are outlined in CWGS-09940.

One possible alternative to coal tar epoxy coatings for use on sheet piling and pipe is fusion-bonded epoxy (FBE) coating. FBE coating is a shop-applied thermoset powder coating used to prevent corrosion on architectural sections such as pipes. FBE coatings are highly cross-linked and have excellent barrier properties. Pipeline applications include soil and immersion exposures. American Society for Testing and Materials (ASTM) standards for epoxy-coated steel products include D 3963, *Specification for Epoxy-Coated Reinforcing Steel Bars*; A 899, *Specification for Epoxy-Coated Steel Wire*; and A 884, *Specification for Epoxy-Coated Steel Wire and Welded Wire Fabric for Reinforcing*. Efforts are currently underway to develop an ASTM standard for FBE coating use on pilings.

Objective

The objective of this research was to evaluate the performance and potential use of fusion-bonded epoxy coating as a replacement for coal tar epoxy coating.

Approach

Four commercially available FBE coatings were factory-applied to steel test plates. The test coatings were evaluated using laboratory tests designed to simulate a variety of exposure environments including fresh and salt water immersion, burial in soil, and atmospheric weathering. After exposure the test panels were evaluated for degree of rusting, blistering, and rust undercutting. The test coatings were also evaluated for resistance to impact damage. Standard Corps of Engineers epoxy systems were used as experimental controls.

Scope

This study was limited to a laboratory evaluation of FBE coatings. Laboratory test exposures can be used to measure the relative performance levels of different coatings. However, care should be taken not to extrapolate the results of laboratory experiments to actual field performance. Field tests should always be conducted to fully validate the use of any coating technology.

Mode of Technology Transfer

It is recommended that the information in this report be used to determine, on a preliminary basis, the suitability of FBE coating for replacing or supplementing coal tar epoxy coating C-200A as specified for use on sheet piling and pipe in CWGS-09940.

2 Procedures

Test Coating Application

Four commercially available FBE coatings were randomly selected for evaluation. No attempt was made to prescreen these materials prior to testing based on reputation, testimonial performance, actual performance, or any other criteria other than generic coating type. Each manufacturer agreed to apply their coatings in their manufacturing facilities. The names of the coating manufacturers and their products are not disclosed in this report. This work was performed to measure the performance envelope of FBE coatings and not to assess the suitability of individual products.

The FBE coatings were applied by electrostatic spray to preheated test panels per the manufacturers' standard operating procedures. Test panels were solvent- and abrasive-cleaned in accordance with SSPC specifications SP 1, *Solvent Cleaning* (1982) and SP 5, *White Metal Blast Cleaning* (1991). Test panels were hot-rolled commercial grade carbon steel measuring 3 in. × 9 in. × 0.125 in. All test panels came from a single lot and were shipped to applicators who performed the surface preparation.

Corps of Engineers Paint Systems No. 16 and 21 were used as experimental controls. System 16 consists of two coats of C-200A, coal tar epoxy coating. System 21 consists of two coats of MIL-P-24441, *Paint, Epoxy-Polyamide, General Specification for* (1991). Coatings were spray-applied to SP 1- and SP 5-cleaned hot-rolled commercial grade carbon steel test panels measuring 3 in. × 9 in. × 0.125 in. Table 1 lists the test and control coatings.

The dry film coating thicknesses of the test and control coatings were measured in accordance to ASTM D 1186, *Standard Test Methods for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Base* (1987). The average dry film thicknesses for each coating system are listed in Table 2.

Selection of Test Methods

Laboratory test methods were selected that simulate the expected service environments for FBE-coated steel. FBE coating is proposed as a substitute for coal tar epoxy

Table 1. FBE and Control Coatings.

Coating System	Primer	Topcoat	Description
System No. 6	SSPC Paint No. 16 (Corps specification C-200A)	SSPC Paint No.16	Coal tar epoxy-polyamide
System No. 21	MIL-P-24441 (Formula150)	MIL-P-24441 (Formula 152)	Epoxy-polyamide
FBE-A	N/A	A	thermoset epoxy
FBE-B	N/A	B	thermoset epoxy
FBE-C	N/A	C	thermoset epoxy
FBE-D	N/A	D	thermoset epoxy

coating. Coal tar epoxy may be used to coat architectural sections such as sheet pile and pipe that will be buried in soil, immersed in fresh or salt water, or exposed to the atmosphere. Cathodic disbondment tests can be used to predict the corrosion resistance at discontinuities in barrier coatings on buried steel in contact with soil. Fresh and salt water immersion are readily replicated in the laboratory using aerated tap water and synthetic sea water. Atmospheric exposure may be simulated using an accelerated test method that cycles the test panels through alternating ultraviolet (UV) radiation and salt fog exposures. Laboratory impact tests using a falling weight can be used to evaluate resistance to damage caused by handling and erection of steel pipe and pile in the field.

Salt Water Immersion

Six test panels of each control and FBE coating were immersed for 112 days in synthetic sea water prepared in accordance with section 7, Salt Solution, of ASTM B 117, *Standard Test Method of Salt Spray (Fog) Testing* (1990). All test panels were

Table 2. Average coating thicknesses.

Coating System	Average Dry Film Coating Thickness (0.001 in)
System No. 6	22.1
System No. 21	6.5
FBE-A	16.2
FBE-B	17.6
FBE-C	16.6
FBE-D	7.2

scribed prior to immersion using a sharp instrument to expose an area approximately one-eighth in. by 2 in. All test panels were evaluated after 7, 60, and 112 days for the degree of rusting and blistering in accordance with ASTM D 610, *Standard Method for Evaluating Degree of Rusting on Painted Surfaces* (1989) and ASTM D 714, *Standard Test Method for Evaluating Degree of Blistering of Paints* (1987). The degree of undercutting was measured after 112 days in accordance with ASTM D 1654, *Standard Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments* (1992).

Fresh Water Immersion

The same tests were performed for panels immersed in fresh tap water as for salt water immersion.

Cyclic Corrosion Weathering

Six scribed test panels of each control and FBE coating were subjected to 14 weeks of cyclic corrosion testing. The test cycle consisted of 1 week of continuous exposure in accordance with ASTM G 53, *Standard Practice for Operating Light- and Water-Exposure Apparatus (Fluorescent UV-Condensation Type) for Exposure of Nonmetallic Materials* (1991) followed by one week of exposure in a salt spray cabinet. The cycle in the G 53 exposure consisted of 4 hours at 60 °C with UV light produced by UV-A bulbs followed by 4 hours of condensation at 50 °C. The salt spray cabinet exposed the test panels to 1 hour of salt spray (6wt percent ammonium sulfate and 0.05wt percent sodium chloride) at 30 °C followed by 1 hour of forced air drying at 40 °C. The test panels were evaluated for degree of rusting and blistering after 2, 4, 8, 12, and 14 weeks. Degree of undercutting was measured after 14 weeks.

Cathodic Disbondment

Method A of ASTM G 8, *Standard Test Methods for Cathodic Disbondment of Pipeline Coatings* (1990) was used to measure the susceptibility to corrosion at holidays and other film defects in a highly conductive electrolyte. Three tests were conducted on each of the FBE and control coatings. The exposed test panels were examined for degree of disbondment.

Impact Resistance

FBE and control coatings were evaluated for resistance to impact in accordance with ASTM G 14, *Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)* (1988) except that flat test substrates were used.

3 Results and Discussion

Salt Water Immersion

Degree of blistering adjacent to the scribe and rusting were determined for the FBE and control coatings after 7, 60, and 112 days in salt water immersion. Rust undercutting at the scribe was measured after 112 days. The results are summarized in Table 3. The rust undercutting data has been converted to integer values between 0 and 10 as described in ASTM D 1654, *Standard Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments* (1992) with the exception that the maximum rather than the mean scribe creepage is used. The blistering data is similarly converted by taking the average of the sum of the blister size and the converted blister density. The converted blister density is an integer value from 0 to 10 with very dense blistering equal to zero and no blistering equal to 10. Rust, blister, and undercut values are the averages of five test specimens for each coating system. The composite score shown in the last column is the sum of numerical rust, blister, and undercut ratings at 112 days. A composite score of 30 corresponds to no coating degradation. The raw data for the salt water immersion tests are presented in Appendix A.

No coating degradation was noted for the FBE or control coatings at 7 days. Blistering adjacent to the scribe was observed for FBE coating D and control system 21 (MIL-P-24441) after 60 days in immersion. At 112 days the density of blistering had increased

Table 3. Salt Water Immersion.

Coating System	7 days Rusting/Blistering	60 days Rusting/Blistering	112 days Rust/Blister/ Undercut/Composite
System No. 6	10/10	10/10	10/10/10/30
System No. 21	10/10	10/6	10/4/8.5/22.5
FBE-A	10/10	10/10	10/10/8/28
FBE-B	10/10	10/10	10/10/7.3/27.3
FBE-C	10/10	10/10	10/10/9.3/29.3
FBE-D	10/10	10/5	10/3.3/5.7/19

for FBE coating D, and both density and size of blisters had increased for control system 21. Blistering adjacent to the scribe may be indicative of inferior long-term performance. The FBE coatings in general show good resistance to blistering in salt water immersion.

Coating film defects resulting from damage during handling and erection are inevitable. Degree of rust undercutting measured in conjunction with coating film defects is an important measure of long-term coating performance. With the exception of FBE coating C, rust undercutting was more pronounced for the FBE coatings than for the controls. Control system 6, coal tar epoxy, was clearly superior by this measure of performance.

Control system 6 had the best overall rating at the completion of the 112 day testing period. Three of the FBE coating systems are superior to control system 21, epoxy-polyamide coating. These three materials provided very good protection in salt water immersion for the duration of the test.

Fresh Water Immersion

The degrees of rusting and blistering were determined for the FBE and control coatings after 7, 60, and 112 days in fresh water immersion. Rust undercutting was measured after 112 days. The results are shown in Table 4. The raw data is presented in Appendix B. The composite score for each test panel is presented in the last column of the table.

Table 4. Fresh Water Immersion.

Coating System	7 days Rusting/Blistering	60 days Rusting/Blistering	112 days Rust/Blister/ Undercut/Composite
System No. 6	10/10	10/6.5	10/5.5/9.5/25
System No. 21	10/10	10/10	10/10/10/30
FBE-A	10/10	10/10	10/10/9.5/29.5
FBE-B	10/10	10/10	10/10/8.8/28.8
FBE-C	10/10	10/10	10/10/9/29
FBE-D	10/10	10/10	10/5.6/5.5/21

All of the test panels had a perfect rust rating of 10 at the completion of testing. Control system 6, coal tar epoxy, was the only coating exhibiting blistering adjacent to the scribe after 60 days. FBE coating D showed blistering adjacent to the scribe after 112 days. The size of blisters, but not the density, had increased for control system 6 after 112 days. With the exception of FBE coating D, the FBE coatings were found to have good resistance to blistering in fresh water.

Control system 21, epoxy-polyamide coating, has marginally superior resistance to rust undercutting at the scribe compared to control system 6 and FBE coatings A, B, and C. FBE coating D has poor resistance to rust undercutting in fresh water immersion.

Control system 21 and FBE coatings A, B, and C, provided excellent protection in fresh water immersion as indicated by their high composite scores. FBE coating D performs marginally in fresh water immersion.

Cyclic Corrosion Weathering

FBE coatings and controls were evaluated for 14 weeks in a cyclic salt fog/UV-condensation corrosion cycle designed to simulate the long-term effects of atmospheric weathering. Test panels were evaluated for rusting and blistering after 2, 4, 8, 12, and 14 weeks. Rust undercutting at the scribe was measured at the completion of the 14-week test. The results are summarized in Table 5. Appendix C contains the raw data for the cyclic corrosion testing.

All of the test panels had perfect rust ratings at the completion of the cyclic corrosion test. Control system 6 showed the best overall performance for the cyclic corrosion test. It suffered the least rust undercutting of any of the coatings and did not blister adjacent to the scribe until the last inspection interval and then only slightly. The performance of control system 21 and FBE coating B followed similar paths, with blistering first visible after 4 weeks that progressively worsened. The measured undercutting was similar for these systems as well.

Cyclic corrosion testing was used to predict the relative performance of the control and test coatings in atmospheric weathering. Overall, system 21 and FBE-B exhibited only fair resistance to degradation in the cyclic corrosion test. FBE-A and FBE-C fared slightly better in this test with no blistering observed for the duration of the test. However, rust undercutting was quite severe for both coating systems and hence overall performance was still only fair. FBE coating D showed poor overall resistance to cyclic corrosion. Resistance to both blistering at the scribe and rust undercutting

Table 5. Cyclic Corrosion Weathering Test.

Coating System	Rusting/Blistering				Rust/Blister/ Undercut/Composite 14 weeks
	2 weeks	4 weeks	8 weeks	12 weeks	
System No. 6	10/10	10/10	10/10	10/10	10/9.3/5.8/25.1
System No. 21	10/10	10/9.2	10/4.4	10/3.7	10/3.7/4.3/18.1
FBE-A	10/10	10/10	10/10	10/10	10/10/1.3/21.3
FBE-B	10/10	10/5.7	10/4	10/3.8	10/4/3.5/17.5
FBE-C	10/10	10/10	10/10	10/10	10/10/3.3/23.3
FBE-D	10/8.2	10/4	10/6.7	10/3.7	10/2/0/12

were poor. Control system 6, coal tar epoxy, had generally good performance for the simulated atmospheric exposure cycle. Blistering was slight and rust undercutting was moderate.

Cathodic Disbondment

Table 6 summarizes the results of the cathodic disbondment tests conducted on the control and test coatings. The radius of disbonded coating is listed for each test panel as well as the average radius for each coating system. The results for each system meet the ASTM test requirement for repeatability. FBE-A, FBE-C, and control system 21 all exhibit the same approximate resistance to cathodic disbondment. FBE-B and control system 6 have slightly lower resistance, while not unexpectedly FBE-D is significantly less resistant to cathodic disbondment.

Different levels of disbondment for different coating systems may not have the same implications in terms of corrosion resistance. While resistance to disbondment as measured by this test may be a positive indicator of performance, it is not the only important characteristic of a coating. The results are meaningful in that they form a basis for comparing the relative resistance of different coating systems to disbondment. For this investigation there is a strong correlation between poor corrosion resistance as determined by immersion and cyclic corrosion tests when compared to the results of the cathodic disbondment test. This is especially evident for FBE-D.

State departments of transportation in Maine (1986) and Ohio (1986) have specified FBE coating on pilings. These states allow a maximum cathodic disbondment of 10 mm as determined by the same test method used for this study. All of the FBE and

Table 6. Cathodic Disbondment Test.

Coating System	Panel Number	Radius (mm)	Average Radius (mm)
System No. 6	17	16.2	16.2
System No. 6	18	16.2	
System No. 6	19	16.2	
System No. 21	31	9.5	12.2
System No. 21	32	14.3	
System No. 21	34	12.7	
FBE-A	A-24	12.7	12.7
FBE-A	A-25	12.7	
FBE-A	A-26	12.7	
FBE-B	B-16	19.8	19.3
FBE-B	B-17	19.1	
FBE-B	B-18	19.1	
FBE-C	C-2	11.1	12.2
FBE-C	C-3	12.7	
FBE-C	C-4	12.7	
FBE-D	D-38	22.2	24.3
FBE-D	D-39	22.2	
FBE-D	D-40	28.6	

control coatings have higher average disbondment radii than required by these states. However, with one exception each of the coatings are within the expected range for interlaboratory reproducibility of the test. For a measured disbondment radius of 10 mm, interlaboratory results should be considered suspect if greater than 22.7 mm. Significantly, only FBE-D is out of the range of interlaboratory reproducibility.

Impact Resistance

Table 7 shows the results of the impact tests. All of the FBE coatings are more resistant to impact damage than the control coatings. The ability of factory-coated architectural sections to resist impact damage is very important. Precoated sections are susceptible to damage during shipping, handling, and erection, and corrosion may proceed rapidly where the coating has been damaged. The very high impact resistance of the FBE coatings is noteworthy and may represent a significant advantage over the standard Corps of Engineers systems in this regard.

Table 7. Impact Resistance Test.

Coating System	Inch-pounds	Joules
System No. 6	70	7.9
System No. 21	125	14.2
FBE-A	>160	>18.1
FBE-B	>160	>18.1
FBE-C	>160	>18.1
FBE-D	>160	>18.1

Ranking of Coating Systems

The composite scores for each of the exposure tests are summed and averaged in Table 8. The rank order positions for the FBE coatings are nearly the same for each of the exposure tests as well as for the cathodic disbondment test. The rank order of the FBE coatings in fresh water immersion is A > C > B > D, in salt water C > A > B > D, for the cyclic corrosion test C > A > B > D, and for cathodic disbondment C > A > B > D. Any one of these tests by itself would appear to be a reasonable predictor of the relative performance of the FBE coatings. Also, each of the tests identified FBE coating D as a significantly lower performance coating. The same cannot be said for the two control coating systems; their rank order positioning, both relative to each other and the FBE coatings, is dependent on the type of test.

It is also interesting to compare the relative performance of the FBE and control coatings by exposure. For the FBE coatings the cyclic corrosion exposure was the most

Table 8. Summary of Composite Scores for Corrosion Tests.

Exposure	Coating System					
	FBE-A	FBE-B	FBE-C	FBE-D	Sys. 6	Sys. 21
fresh water	29.5	28.8	29	21	25	30
salt water	28	27.3	29.3	19	30	22.5
cyclic corrosion	21.3	17.5	23.3	12	25.1	18.1
average score	26.2	24.5	27.2	17.3	26.7	23.5

severe followed by salt water immersion and then fresh water immersion. Control system 6 was significantly better in salt water than in fresh water immersion; the converse is true of system 21. Among FBE coatings A, B, and C, performance in salt and fresh water immersion was more consistent than either of the control coatings. This implies that the FBE coatings may be more universally applicable to a wider range of exposures than either of the control systems.

The average composite scores for the immersion and cyclic corrosion tests are not significantly different for FBE coatings A, B, and C, nor are they significantly different as a group from the control systems. FBE coating D is significantly worse in terms of corrosion protection and cathodic disbondment than FBE coatings A, B, and C. The measured dry film thicknesses for FBE coatings A, B, and C are quite close while the average thickness of FBE coating D test panels was much less. For FBE coatings there appears to be a correlation between film thickness and performance. System 21 test panels had nearly the same average film thickness as FBE coating D test panels. However, examination of the rank order of FBE coating D and system 21 for each exposure does not indicate a correlation between the film thickness of FBE and other epoxy coatings.

Film thickness also appears to play a role in the mode of coating failure. For the thick film coatings A, B, C, and control system 6, the average rust undercutting and blister numerical scores are 7.1 and 9.1, respectively. For the thin film coatings FBE-D and system 21 the averages are 5.7 and 4.8 for undercutting and blistering. Blistering is a more important contributor to overall coating degradation for the thin film systems. This also is true of the FBE coatings as a group, with average blister scores of 9.3 and 3.6 and average undercut scores of 6.7 and 3.7 for thick and thin film coatings, respectively.

4 Conclusions and Recommendations

Salt water and fresh water immersion and cyclic corrosion tests were run to predict the long-term corrosion resistance of the FBE coatings relative to standard Corps of Engineers paint systems. In salt water immersion three of four FBE coatings had very good performance. System 6, coal tar epoxy coating, was slightly better and system 21, epoxy-polyamide coating, was not as good as the three performing FBE coatings. In fresh water immersion the same three FBE coatings again exhibited very good corrosion protection. System 21 was slightly better and system 6 was not as good as these FBE coatings. For the cyclic corrosion resistance test used to predict coating performance in atmospheric exposures, two of the four FBE coatings had good corrosion resistance, better than system 21. However, control system 6 performed significantly better than both the good and lesser performing FBE coatings. The better performing FBE coatings may be expected to provide similar levels of corrosion protection in immersion and atmospheric exposure in comparison with standard Corps systems.

Cathodic disbondment tests were conducted to help predict the relative resistance to coating disbondment in soil exposures. Two FBE coatings performed equally as well as system 21 and only one FBE coating was significantly poorer than the other coatings. FBE coatings may be expected to exhibit similar levels of corrosion resistance in soil exposures in comparison with standard Corps systems.

The FBE coatings have superior resistance to impact damage. FBE-coated architectural sections should be less prone to impact damage caused during shipping, handling, and installation than items coated with standard Corps systems. Coatings that are more resistant to impact damage may exhibit superior long-term performance.

All of the corrosion resistance tests produced roughly the same rank order for the FBE coatings. This coupled with the fact that clear differences exist between the high- and low-performing FBE coatings indicates that any one of these tests may be used to quickly and accurately assess the performance of candidate FBE coatings for a variety of exposures. It is also noteworthy that the performance of the FBE coatings is consistent between the various exposure environments, which is not the case for the control coatings. This implies that the FBE coatings may be more universally applicable than the control coatings.

There is a clear correlation between performance and coating thickness for the FBE coatings. Thin film FBE coatings have significantly reduced levels of corrosion and cathodic disbondment resistance. There is also a correlation between film thickness and mode of coating failure for all of the coatings. Thick film coatings are much less likely to exhibit blistering than the thin film systems.

The overall laboratory performance of the high-performing FBE coatings is roughly equivalent to that of the control coatings. The high-performing FBE coatings are nearly as good as the best control system for each laboratory exposure. FBE coatings warrant further investigation to determine their performance in the field, and a test program to evaluate the use of FBE-coated pile exposed to soil, atmospheric weathering, and immersion environments is recommended. An investigation of the damage caused by driving the pile should also be conducted, and further information on field repair is needed. The study should include analyses of life-cycle cost and quality control. FBE coatings may offer life-cycle cost reductions, lowered worker exposures to toxic substances, and improved environmental quality through reduced solvent emissions from painting. Powder coating is already significantly established in the manufactured goods sector of the U.S. economy and increased use as an architectural coating is likely.

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Appendix A: Salt Water Immersion Data

Coating System	7 days (rusting/blistering)	60 days (rusting/blistering)	112 days (rust/blister/ undercut)
FBE-A	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-A	10 / 10	10 / 10	10 / 10 / 0
FBE-A	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-A	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-A	10 / 10	10 / 10	10 / 10 / 0
FBE-A	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0-3/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0-1/32
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0-1/32
FBE-D	10 / 10	10 / #2F	10/ #2D/ 0-1/32
FBE-D	10 / 10	10 / #2F	10/ #2D/ 0-1/32
FBE-D	10 / 10	10 / #2F	10/#2M/ 0-4/32
FBE-D	10 / 10	10 / #2F	10/#2M/ 0-7/32
FBE-D	10 / 10	10 / #2F	10/#2M/ 0-5/32
FBE-D	10 / 10	10 / #2F	10/#2M/ 0-6/32

No. 6	10 / 10	10 / 10	10 / 10 / 0
No. 6	10 / 10	10 / 10	10 / 10 / 0
No. 6	10 / 10	10 / 10	10 / 10 / 0
No. 6	10 / 10	10 / 10	10 / 10 / 0
No. 6	10 / 10	10 / 10	10 / 10 / 0
No. 6	10 / 10	10 / 10	10 / 10 / 0
No. 21	10 / 10	10 / #4F	10/#2M/ 0-1/32
No. 21	10 / 10	10 / #4F	10/#2M/ 0-2/32
No. 21	10 / 10	10 / #4F	10/#2M/ 0-1/64
No. 21	10 / 10	10 / #4F	10/#2M/ 0
No. 21	10 / 10	10 / #4F	10/#2M/ 0-2/32
No. 21	10 / 10	10 / #4F	10/#2M/ 0

Appendix B: Fresh Water Immersion Data

Coating System	7 days (rusting/blistering)	60 days (rusting/blistering)	112 days (rust/blister/ undercut)
FBE-A	10 / 10	10 / 10	10 / 10 / 0
FBE-A	10 / 10	10 / 10	10 / 10 / 0
FBE-A	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-A	10 / 10	10 / 10	10 / 10 / 0
FBE-A	10 / 10	10 / 10	10 / 10 / 0
FBE-A	10 / 10	10 / 10	10 / 10 / 0
FBE-B	10 / 10	10 / 10	10 / 10 / 0-5/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0
FBE-B	10 / 10	10 / 10	10 / 10 / 0-1/32
FBE-B	10 / 10	10 / 10	10 / 10 / 0
FBE-B	10 / 10	10 / 10	10 / 10 / 0
FBE-B	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0
FBE-C	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-C	10 / 10	10 / 10	10 / 10 / 0-2/32
FBE-D	10 / 10	10 / 10	10/#3M/ 0-4/32
FBE-D	10 / 10	10 / 10	10/#3M/ 0-3/32
FBE-D	10 / 10	10 / 10	10/#2F/ 0-8/32
FBE-D	10 / 10	10 / 10	10/#3M/ 0-4/32
FBE-D	10 / 10	10 / 10	10/#2F/ 0-4/32
FBE-D	10 / 10	10 / 10	10/ 10/ 0-5/32

Appendix C: Cyclic Corrosion Test Data

Coating System	2 weeks (rust/blister)	4 weeks (rust/blister)	8 weeks (rust/blister)	12 weeks (rust/blister)	14 weeks (rust/blister/ undercut)
FBE-A	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/2
FBE-A	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 3/8-1
FBE-A	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 0-1/2
FBE-A	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/16-1
FBE-A	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 0-1/2
FBE-A	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 0-1/2
FBE-B	10 / 10	10 / #3F	10 / #2M	10 / #2M	10/ #2M/ 3/32-7/32
FBE-B	10 / 10	10 / #2F	10 / #2M	10 / #2M	10/ #2M/ 1/8-5/16
FBE-B	10 / 10	10 / #2F	10 / #2M	10 / #2M	10/ #2M/ 3/16-5/16
FBE-B	10 / 10	10 / #2F	10 / #2M	10 / #2D	10/ #2D/ 1/4-1/8
FBE-B	10 / 10	10 / #3F	10 / #2M	10 / #2M	10/ #2F/ 1/16-1/4
FBE-B	10 / 10	10 / #3F	10 / #2M	10 / #2F	10/ #2F/ 0-7/32
FBE-C	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/8-1/4
FBE-C	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 3/32-1/4
FBE-C	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 0-1/32
FBE-C	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/8-5/8
FBE-C	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 7/32-35/32
FBE-C	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/8-3/8
FBE-D	10 / 10	10 / #2F	10 / #2M	10 / #2D	10/ #2D/ 3/4
FBE-D	10 / 10	10 / #2M	10 / 10	10 / #2D	10/ #2D/ 1
FBE-D	10 / 10	10 / #2D	10 / 10	10 / #2M	10/ #2D/ 1
FBE-D	10 / 10	10 / #2F	10 / 10	10 / 10	10/ 10/ 1 1/2
FBE-D	10 / #3M	10 / #2M	10 / #2D	10 / #2D	10/ #2D/ 3/4
FBE-D	10 / #3M	10 / #2D	10 / #2M	10 / #2D	10/ #2D/ 7/8

No. 6	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 0-3/32
No. 6	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/16-1/4
No. 6	10 / 10	10 / 10	10 / 10	10 / 10	10/ #4F/ 0-3/32
No. 6	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 3/32
No. 6	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/16-3/32
No. 6	10 / 10	10 / 10	10 / 10	10 / 10	10/ 10/ 1/16
No. 21	10 / 10	10 / 10	10 / #6M	10 / #6M	10/ #6M/ 1/16-3/16
No. 21	10 / 10	10 / 10	10 / #6F	10 / #6F	10/ #6F/ 1/16-3/16
No. 21	10 / 10	10 / 10	10 / #4M	10 / #2D	10/ #2D/ 1/8-1/4
No. 21	10 / 10	10 / 10	10 / #3M	10 / #3D	10/ #3D/ 1/16-1/4
No. 21	10 / 10	10 / #5M	10 / #3M	10 / #2D	10/ #2D/ 1/4
No. 21	10 / 10	10 / 10	10 / #3M	10 / #3D	10/ #3D/ 3/16-1/4

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